F2016-APSE-010

THEORETICAL AND EXPERIMENTAL STUDY OF THE STRENGHT OF POST-ACCIDENT COACHES STRUCTURES.

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KEYWORDS – Collision repair, coaches structures, energy absorption, bending test, Finite Elements Method.

ABSTRACT

Vehicles repair after an accident and the quality assurance of the repair is a major safety issue. If the vehicle type category is M3, collective road transport vehicles, there is an additional concern due to their high number of occupants, the responsibility of third parties transport and the severity of some type of collisions such as rollovers. The objective of this work is to quantify the loss of energy absorption capabilities of the structural steel profiles of rectangular hollow section used in the construction of these vehicles and model this behaviour with a FEM software.

In order to model the behaviour of the structural profiles after repair with a FEM model, there is a need of quantify the loss of energy absorption in real samples.
The deformation energy has been measured by means of bending tests and calculating the bending moment vs bending angle curve. The load has been applied to reach 5, 10 and 20 permanent bending angles, representing those rollover structural deformations found on coach collisions of different severities. All test specimens have been straightened and bended up to 20 degrees some in the same bending direction as initial bend test and some in the opposite direction. Then, computer simulations are made until the behaviour found in the tests is modelled with the FEM model.

The results show a significant loss of strength of the profiles and the consequent loss of deformation energy. It has been developed a method to achieve the same results with a FEM model.

The greatest limitations of this study are, on one hand, the number of tests that can be carried out, because it is mandatory the test samples are made from the same cast steel in order to eliminate the effects from variations in material properties. On the other hand, the origin of the loss of mechanical properties is not clear at this point; it could be by geometrical or material property changes.

In this paper, the loss of energy absorption after repairing has been quantified. Furthermore, it is presented the results of modeling this change of behavior with a FEM model. The values of energy absorption in the test samples demonstrate how it should be defined requirements for repaired buses and coaches after their repair of structural damages in collisions.

INTRODUCTION.

Rollovers are the most severe accidents of coaches and their consequences have required specific countermeasures to diminish the risks in case of accident. Being the most significant of these countermeasures the entry into force of UNECE Regulation 66 Revision 00 in December 12th 1986 (1). Matolcsy (2007) (3) concluded that R66.00 survival space concept and requirements were very effective (all casualty rate is 3 - 4 times lower, the fatality rate is lower with one order (10 times) when the survival space remains intact). Since that date, several improvements to the Reg. 66 requirements have been established, and the most relevant of them has been the consideration in Revision 01 (2) of the 50% of the mass of the passengers as consequence of the mandatory installation, and use, of the seat belts. The entry into force, in November 2005, of this revision has meant a 30% average increase of energy absorption requirement for the superstructure (García et al. 2006) (5). In this work, it will be demonstrated that flexural bending and subsequent straightening of rectangular hollow sections can cause a structural weakening even higher than above-mentioned value (30%).

The value of the analyzed vehicles (coaches) is high, and it is still high even after having experienced an accident if mechanical damages are not severe enough. For this reason, coaches that have been involved in an accident (e.g. rollover) are often repaired straightening their structures in repair benches. To date it has not been considered in any regulation, the establishment of repair or inspection criteria for structures of coaches after experiencing an accident.

In Spain, in 2014, a coach suffered an unfortunate accident with rollover and subsequent fall down a slope (14 deceased passengers). The same vehicle had experienced a previous lateral rollover accident in 2010. It should be noted that the preliminary accident did not cause severe structural deformations and, especially, that the severity of the second rollover accident make it impossible to establish relationships between the accident severity and the repair.

For all above-mentioned arguments, it has been considered a need to evaluate, experimentally in a first step, the loss of energy absorption capabilities of repaired rectangular hollow sections. Also, a methodology to simulate this loss of mechanical properties in FEM models is mandatory, as the need of understand and investigate the loss of energy absorption capability in profiles with different section without the cost of having to run tests. In further steps of this research it will be assessed the best procedures and practices to proceed to coach structures repair.

METHODOLOGY.

This research consists of the following two phases: The first one (phase I) is the experimental study of the behavior of the steel rectangular hollow sections by means of bending tests. Phase II has consisted in emulate the behavior found in the tests with FEM models as faithfully as it can be.

Experimental Study of the Steel Profiles of Rectangular Hollow Section by Bending Tests (Phase 1).

The first step of the methodology is the determination of the characteristic Moment vs Angle curves and the absorbed energy by the profiles in bending tests applying the methodology proposed by García (1990) (4). These tests were performed according to the following procedure:

- STEP 1: the profile is bended to reach 5, 10 or 20 degrees of permanent deformation.
- STEP 2: the profile is straightened to its original geometry.
- STEP 3: the profile is bended up to 20 degrees in the same or the opposite direction than the first deformation.

In order to fulfill the objective of this phase and determine the behavior, six profiles were tested as indicated before: two with 5 degrees of permanent first deformation, two with 10 and two with 20 degrees; in the three cases, one of every pair was bended in the same direction than the first deformation and the other in the opposite.

With the data of the displacement and load time histories obtained in the tests, the calculation of Moment – Angle and Absorbed energy curves can be carried out.

All test samples were manufactured using the same steel casting in order to eliminate the effects from variations in material properties.

Modeling the Behavior With FEM Models (Phase 2).

The main objective of this phase is to achieve with a FEM model, the most similar Moment – Angle curve to the ones obtained in the previous phase. In order to do this, there have been studied several paths with ANSYS software, including different element types and element technologies. The options that have been studied at this point of the research are in the next table:

Case	Material	Element Type	Element Technology
a	Bilinear Kinematic	SHELL 181	Reduced Integration
b	Bilinear Kinematic	SOLID 185	Reduced Integration
c	Bilinear Kinematic	SOLID 185	Enhanced Strain
d	Bilinear Kinematic	SOLID 186	Reduced Integration

Table 1. FEM model options.

The methodology is similar to the one in the tests. The profile in the model has a displacement applied in one of the ends and is constrained in the other end. For all the cases above, the procedure was:

- STEP 1: Apply the necessary displacement in one of the ends to achieve 20 degrees of plastic deformation.
- STEP 2: Import the deformed mesh into another database and applied the opposite displacement to straighten the profile. In this step, the yield stress of deformed elements is multiply with a factor of 0.9 to simulate the loss of mechanical properties.
- STEP 3: Import the deformed mesh into another database and applied the necessary displacement to bend the profile 20 degrees in the same direction than the first deformation. The yield stress of deformed elements is multiply with a factor of 0.7 to simulate the loss of mechanical properties.
- STEP 4: Repeat the previous step, but applying the displacement in the opposite direction.

Once all the steps have been done, the Moment – Angle curves are compared between the FEM models and the tests from phase 1.

RESULTS.

Phase 1.

The next figures represent the Moment vs Bending angle curves of every profile tested, being:

- Blue curve: First deformation.
- Green curve: Repair.
- Red curve: Second deformation.

In every case, the curves are compared between both with the same first deformation bending angle but contrary direction in second deformation.

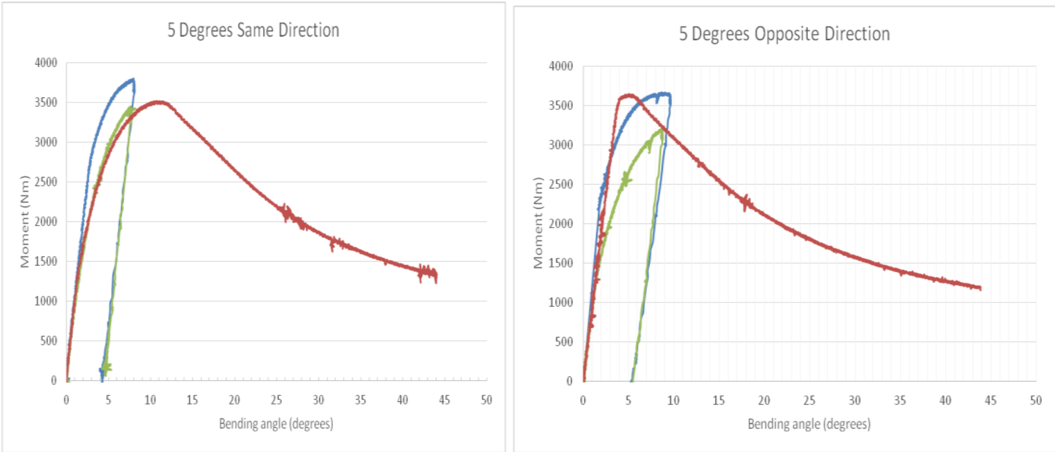

Figure 1. Moment – Bending angle. 5 degrees first deformation.

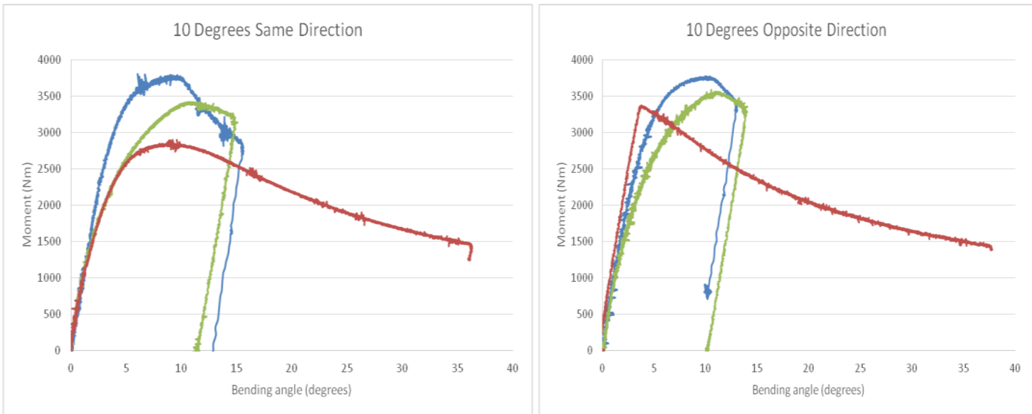

Figure 2. Moment – Bending angle. 10 degrees first deformation.

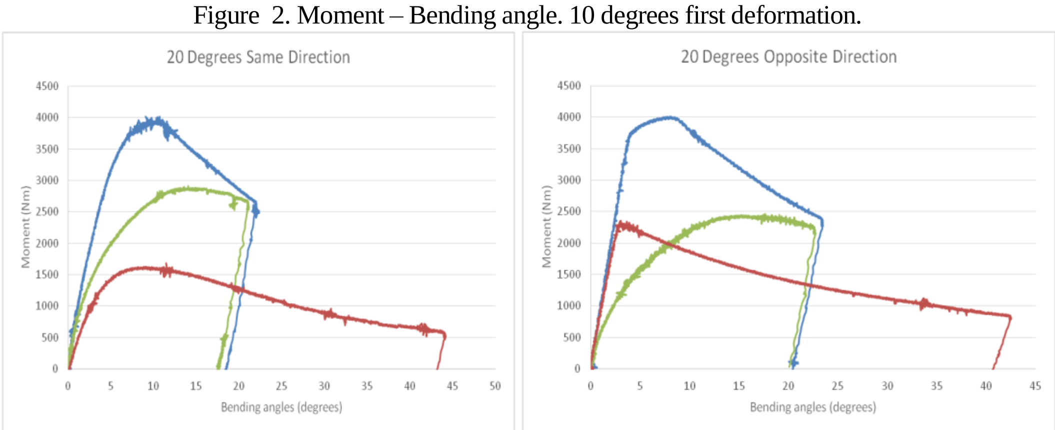

Figure 3. Moment – Bending angle. 20 degrees first deformation.

In order to understand the figures above, the next tables quantified the loss in energy absorption capability and maximum moment, which are the two values that give a better understanding of the behavior.

Table 2 compares the maximum moment reached in the second deformation with the one reached by the pattern sample, which is the same value of the maximum moment in the first deformation of all the samples.

	5º Same direction	**5º Opposite direction**	**10º Same direction**	**10º Opposite direction**	**20º Same direction**	**20º Opposite direction**
Maximum Moment (Nm)	3580	3688	2834	3376	1186	2298
Percentage	88	91	70	83	42	57

Table 2. Comparison of maximum moment.

Table 3 compares the absorbed energy in the second deformation at the point of 30 degrees in plastic region. The absorbed plastic energy during all the process is in figure 5.

	5º Same direction	**5º Opposite direction**	**10º Same direction**	**10º Opposite direction**	**20º Same direction**	**20º Opposite direction**
Absorbed Energy (J)	1324	1342	1159	1245	657	788
Percentage	88	89	77	82	44	52

Table 3. Comparison of absorbed energy.

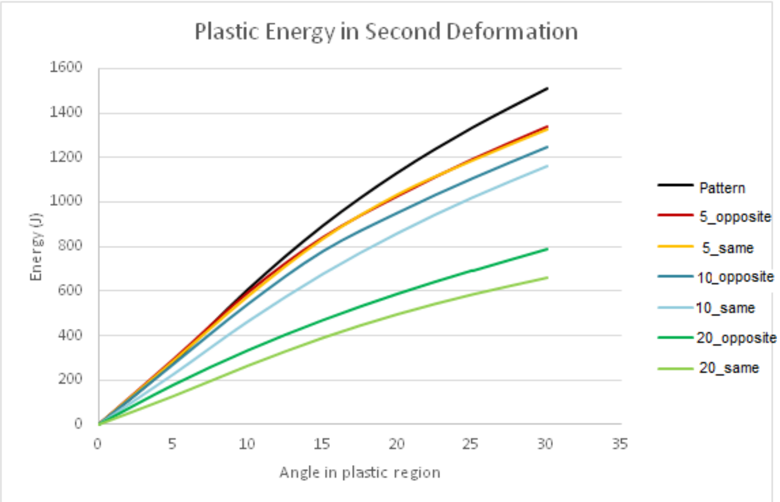

Figure 4. Absorbed plastic energy in second deformation.

Phase 2.

The results of the phase two are represented in the next figures, compared to the experimental curves of phase 1 and between two cases (a, b, c or d). The order of the figures is: first deformation, repair, second deformation in the same direction and second deformation in the opposite direction.

Cases a (Red) – b (Green) – experimental (Black).

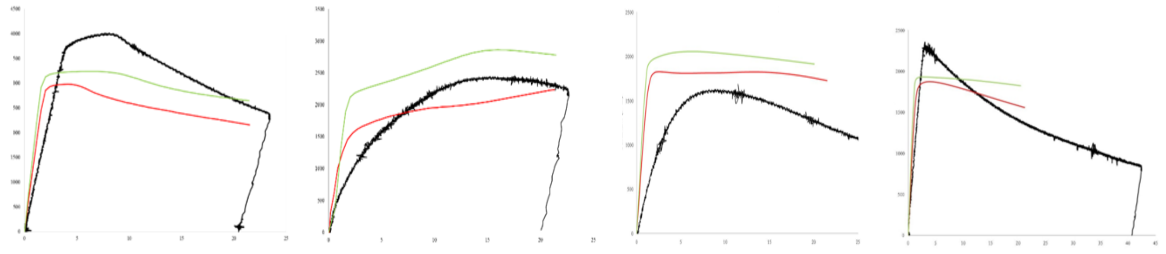

Figure 5. Comparison cases a – b – experimental.

Cases b (Red) – c (Green) – experimental (Black).

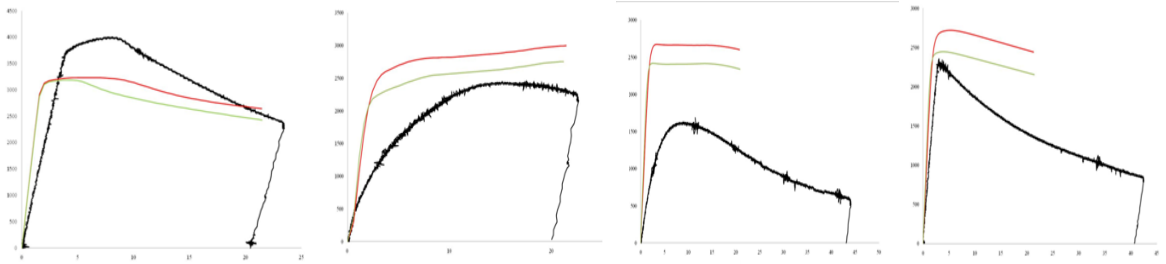

Figure 6. Comparison cases b – c – experimental.

Cases c (Red) – d (Green) – experimental (Black).

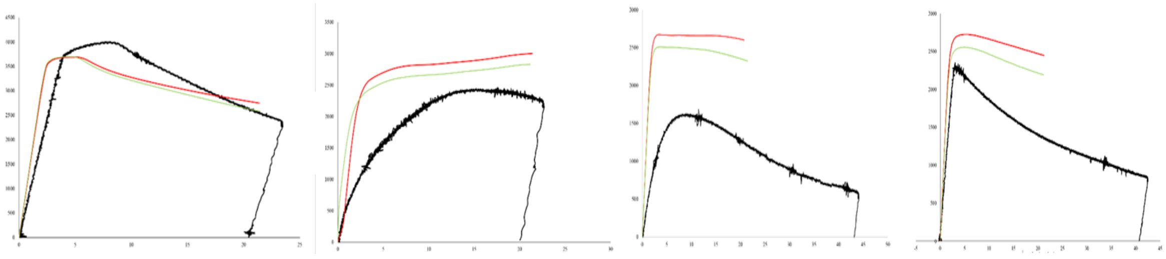

Figure 7. Comparison cases c – d – experimental.

DISCUSSION.

The results of phase 1 show a loss of strength in the profiles tested during and after the repair compared to their initial characteristics. This loss is greater as the bending deformation angles are increasing, reaching in the 20 degrees deformation samples a loss of 50 per cent.

This loss in energy absorption can be explained with the Moment vs bending angle curves, comparing the first and second deformation curves. In the second one, the maximum moment is lower, reducing the area beneath the curve and so the energy as well. However, the slope of the curve in the plastic region (after the maximum moment), is minor in the second deformation.

Another point to highlight is the different behavior depending on the direction of the second deformation. If the second deformation is in the opposite direction of the first one, the maximum moment does not decrease as much as it does when the deformation is in the same direction; so, the energy absorption capability depends not only on the bending angles but on the direction of the bending.

The results of phase 2 show that the methodology proposed in this paper recreate the behavior of the profiles, but not yet with the accuracy required. Case b, SOLID185 with reduced integration, is the worst option because of the stiffness of the element itself. This can be improve by changing the element technology to enhanced strain (case c), or by increasing the integration points with a higher order element (case d). The best option should be case d, but the computational cost is much greater than in any other case.

It is major issue then, to define the requirements of a repaired coach structure and achieve a methodology to represent faithfully the behavior of a repair profile.

CONCLUSIONS.

It has been measured the loss of energy absorption capability of rectangular hollow sections after experimenting flexural bending permanent deformation and a subsequent repair, showing a significant loss above 10 degrees of plastic deformation.

The methodology proposed to model the behavior of repaired profiles with FEM is a good approximation but not enough accurate. However, it is in the right direction and it will be improved in further steps of this research.

Current analytical models, representative of the flexural bending behavior of rectangular hollow sections, are not adequate to represent the absorption capability of repaired by straightening profiles.

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